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## Accelerating phase displacement prediction and 3D rockfall modelling of the large Gallivaggio rockfall

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Rockfalls are severe and common dangerous events in mountain areas which are strongly controlled by geological and weather conditions. Remotely sensed data allows to identify slowly moving block volumes and to characterize the evolution towards collapse. The commonly adopted approaches for time to failure estimations generally rely on the inverse velocity approach. In this study we investigate the capabilities of a viscoplastic model to simulate the progressive evolution of the block instability with time. We use the monitored time series to calibrate the model parameters and then we pass to the modeling of the entire rockfall events and to the design of mitigation countermeasures. To this aim we study the May 29<sup>th</sup> 2018 Gallivaggio rock fall (San Giacomo Filippo, Sondrio, Italy) when about 5,000 m<sup>3</sup> of rock detached from a 400 m high cliff, causing considerable damage to the area of the Sanctuary of Gallivaggio and closure of the main mountain route (S.S.36).

The area was monitored by the Regional Environmental Protection Agency since 2011 by using a ground-based radar (GB-InSAR, LisaLab srl), and it was affected by a 150 m<sup>3</sup> rockfall event in the last months of 2019.

GB-InSAR data, multiple laser scanner surveys and drone images of the rock cliff recorded before the event allow to identify the source area, to define and characterize the potentially detachable block volumes and their evolution through time. Thanks to the continuous GB-InSAR monitoring which started well before the event, we calibrated the parameters of a 1d multi-block model whose behaviour is governed by time-dependent visco-plastic constitutive law based on the Perzyna's approach. This model is subsequently employed to reproduce the mechanical response of the block masses until their detachment from the vertical wall by using different constitutive laws.

At the same time, the comparison between the size distributions of the detached and the deposited blocks and the dust sampling and characterization allowed us to evaluate the degree of comminution due to fragmentation. This information, which is rarely available, made possible to calibrate the fragmentation algorithm of the code HY-STONE, which simulates fragmentation of the falling blocks overcoming a certain energy threshold and the dynamic behaviour of the resulting fragments. We first applied the code to replicate the rockfall events, being able to simulate the large spreading of the block that was impossible to simulate without the

fragmentation algorithm. Then we applied this modelling approach for the design of a ditch-embankment countermeasure, simulating different scenarios with and without fragmentation. The results show that fragmentation induces an increase in the number of blocks impacting the embankment, in the heights, and in the velocity, but a decrease of the kinetic energy since each fragment has a smaller mass than the original blocks.